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The place of new industries: the case of fuel cell technology and its technological relatedness to regional knowledge bases

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Abstract

The evolutionary turn in economic geography has proposed that regional diversification is a path-dependent process whereby new industries grow out of preexisting industrial structures through technologically related localized knowledge spillover. This paper examines if this also applies for industries developed around emerging radical technology. I develop a new measure for technological relatedness between the knowledge base of the region and that of a radical technology, namely, fuel cells. It is demonstrated that even in the case of a high degree of radicalness and discontinuity, knowledge generation is still cumulative in its spatial and cognitive dimensions, corroborating the evolutionary thesis.

Key words: evolutionary economic geography, radical innovation, regional branching, technological relatedness, fuel cell technology

JEL classifications: C23, R11, R12, Q55

1. Introduction

Discussions on the emergence of new regional industrial paths have gained renewed interest in the field of economic geography. Over the last couple of decades the field of economic geography has experienced what has been called an ‘evolutionary turn’ (Grabher, 2009; see, e.g., Boschma and Martin, 2010; Essletzbichler and Rigby, 2007; Boschma and Martin, 2007; Martin and Sunley, 2006) inspired by the field of evolutionary economics (Nelson and Winter, 1982; Freeman, 1994). This turn has brought about a renewed interest in the question of how we can explain the emergence of new industries and their spatial manifestation as a process of regional path dependency (Martin and Sunley, 2006). Boschma and Frenken (2011) argue that technological relatedness, understood as cognitive proximity, enhances knowledge transfers and sharing from preexisting regional activities to emerging industrial activities within regional borders. Thus, technological relatedness becomes an important enabling factor for the creation of new variety and formation of new regional industrial paths (Boschma and Frenken, 2011; Neffke et al., 2011).

This paper contributes to this scope of the economic geography literature in three ways. Firstly, it is unclear to what degree localization of radically new industries, based on radical technology development, is likewise driven by technologically related knowledge spillover from preexisting regional economic activities. Since radical technology is characterized by a high degree of discontinuity in production and marketing systems and a strong dependency on knowledge produced in R&D departments (see Freeman, 1994; Freeman and Perez, 1988), some scholars (Storper and Walker, 1989) have argued that new industries experience relative ‘freedom’ to locate in a large number of regions. According to Storper and Walker, locational freedom is achieved because new industries are less constrained by specific locational resources and rely to a higher degree on their own creative ability to generate or attract a supportive local environment than is the case for established industries. A refinement of this argument has been made by Boschma and van der Knaap (1997) and Boschma and Lambooy (1999), who argue that the spatial indeterminacy of new industries is limited to regions with useful and beneficial generic resources. Hence, the major contribution of this paper is to investigate and clarify, through an empirical analysis of the localization of radical fuel cell technology, whether or not radical technology development takes place in regions with technologically related generic resources.

Secondly, following Boschma and van der Knaap's (1997) argument that localization of new industries is triggered by a set of localized generic resources, an additional objective of this paper is to expand our understanding of the character of such resources. Boschma and van der Knaap distinguish between general and specific resources and claim that new industries only benefit from a certain combination of generic resources, such as basic knowledge and skills. Previous research has shown that in the case of the automotive industry, the presence of related industries in certain regions was in fact beneficial for the early localization of the British car industry (Boschma and Wenting, 2007). Moreover, Neffke et al. (2011) have shown that industries are more likely to enter regions with technologically related industries and that existing industries are more likely to exit regions where other industries are not technologically related. In this paper I do not focus on classes of industries but investigate the presence of a portfolio of technologically related knowledge fields that together add to the knowledge base of fuel cell technology. By decomposing the availability of generic resources into specific knowledge fields relevant to fuel cell technology, the analysis becomes more detailed in its measure of technological relatedness. This enables the analysis to reveal the importance of specific knowledge fields (over others) and to distinguish between degrees of technological relatedness.

Thirdly, this paper develops a new way of measuring technological relatedness based on the (evolving) knowledge base of a nascent technology area. The main dataset is a regionalized database of patent applications filed under the Patent Cooperation Treaty (OECD, June 2010), which makes it possible to measure fuel cell patenting and fuel cell technologically related patenting for a sample of European regions, where patent activity is seen as a proxy of knowledge production and, hence, works as a measure of competences and skills that are present in a given region within specific knowledge areas. Eight knowledge fields that form part of the fuel cell knowledge base are identified as fuel cell–related knowledge, and the same database makes it possible to measure the level of knowledge production within these eight knowledge fields for each region over a 15-year period. This is a much more precise way of measuring technological relatedness than industrial classes have previously allowed. Additionally, although patent data have been criticized for their many shortcomings, another clear advantage of measuring knowledge fields as an alternative to industry classes is the possibility to analyze localization patterns of emerging technology, which often drowns in industrial classification systems.

This paper focuses on the emerging fuel cell technology, which is an environmentally friendly energy technology. A fuel cell is an electro-chemical device that generates electricity based on a chemical reaction between oxygen and hydrogen. Fuel cell technology is radical because it has the potential to replace incumbent energy technologies and as such results in technological discontinuities (Garcia and Calantone, 2002). It functions as an entirely new chemical process of energy conversion and consequently builds upon a new set of scientific and technical principles, which requires the buildup of a new knowledge base (Bourgeois and Mima, 2003; Avadikyan et al., 2003). Since the early 1990s fuel cell technology development has gained momentum in its technical achievements and is seen as one of the promising alternatives to replace fossil fuel–based energy technologies in the long term. This has happened as a result of an increasing interest in the technology by various types of actors. In the early years these actors consisted mainly of universities and core developers of fuel cell stacks and fuel cell systems, such as electrical battery manufacturers or new specialized firms (Bourgeois and Mima, 2003). In later years firms further downstream become increasingly involved in fuel cell technology development, mirroring a diverse range of application opportunities and markets within stationary power, automotive, and portable equipment.

The paper is structured as follows. The next section describes the theoretical conceptualization on which the paper builds. This section begins with a brief distinction between incremental and radical innovation, and defines the concept of 'radically new regional industrial paths'. Then the processes of early industrial localization are discussed, distinguishing between the 'window of locational opportunity' interpretation and the concept of 'regional branching'. Section 3 describes some characteristics of fuel cell technology, and section 4 introduces the data, method, and model used, including a thorough description of the measure of 'technological relatedness'. Section 5 presents the results, and the concluding section 6 sums up the findings and points the direction for future research.

2. Theory and Conceptualization

Radically new regional industrial paths

We first define the very object this paper focuses on: emerging regional industrial paths based on radical technology, defined here briefly as new industries that build around a radical technology and emerge within the borders of a given region.

Although a plethora of definitions of innovation types is used in innovation studies (Garcia and Calantone, 2002), a simple distinction between incremental and radical technological change is widely accepted to capture the main variations. Incremental innovations occur continuously and are cumulative of nature within technological trajectories (Nelson and Winter, 1982; Freeman, 1994; Dosi and Orsenigo, 1988). They take place within firms or within clusters of firms that are closely linked to each other and, hence, in a geographical respect are perceived to be strongly influenced by preexisting patterns of economic activities (Boschma and van der Knaap, 1997). In other words, incremental changes to products and processes take place where firms are located and are often driven by learning by doing and learning by using mechanisms.

On the other hand, radical innovations often lay the ground for totally new products or processes, generating paradigmatic changes (Dosi, 1982, 1988). Radical innovations are of a discontinuous nature and are argued to spur the emergence of new industries or firms that have the potential to disrupt incumbent industries and firms. In that respect radical innovation is usually perceived to cause discontinuity in the economic system and, by evolutionary economic geographers, to cause instability in the economic landscape (Boschma and van der Knaap, 1997). It also follows that in the early stages of radical technological innovation, uncertainty is very high (Freeman and Perez, 1988), and the technology requires years of development and improvements.

When new industries emerge based on a radical technology it forms what is here called a radically new industrial path. This paper is concerned with where in space the new industrial path is located, and hence terms it a radically new regional industrial path. A new industry may emerge in a number of regions at the same time or slightly separated in time. However, in our definition of radically new regional industrial paths it is important to highlight that the new industry builds on radical technology development and as such is not only new to the region but also *new to the world*.

In the following, a theoretical conceptualization about the localization of radically new industrial paths is outlined, beginning with the notion of 'windows of locational opportunity' (WLO) (Storper and Walker, 1989) and continuing with an alternative approach based on the term 'regional branching' (Boschma and Frenken, 2011).

Early industrial localization through locational freedom

The discontinuous nature of radical technology has caused economic geographers to argue that the spatial formation of new industries occurs relatively independently from economic structures and practices (Storper and Walker, 1989). Storper and Walker (1989) argue based on the WLO concept[1] (Scott and Storper, 1987) that localization of new industries is rather independent from preexisting industrial structures. The presumption is that an emerging industry that bases its development on a radical technology has such unique requirements that any preexisting locational conditions will hardly meet these requirements (Storper and Walker, 1989; Boschma, 1996). Instead, it is claimed that when a new industry emerges, firms experience a level of 'locational freedom' to locate in a large number of places because their future depends to a higher degree on their own ability to shape a supportive environment (e.g., labor skills, suppliers, buyers) than on a set of specific localized resources. Accordingly, leading firms in emerging industries are to a larger extent dependent on their capability to create their own favorable locational conditions than on specific initial conditions provided by the existing settings in a region. Although Storper and Walker do point out that locational freedom has limits and that we will not see new industries develop in relatively unindustrialized regions (Storper and Walker, 1989), their overall argument is towards a high degree of spatial indeterminacy of new industrial localization.

Hence, the main shortcoming of the WLO framework is that it does not pay much attention to the possibility that new industries are linked to already existing industrial structures in a region as a result of regional path dependency. Contrary to the emphasis of the WLO approach on spatial indeterminacy, the later work of Boschma and others modifies this understanding and suggests that the spatial emergence of new industries is not an entirely accidental process (Boschma and Martin, 2007; Boschma and Frenken, 2011). Boschma and van der Knaap (1997) and Boschma and Lambooy (1999) question the inherent assumption in the early WLO concept that new industries develop from scratch (Boschma, 2007). They argue that new industries build on a set of generic, location-specific resources that have the potential to trigger new industries to emerge.

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[1] The WLO framework emerged in the late 1980s out of an interest in explaining why old industrial regions since the 1960s and onwards experienced severe problems of deindustrialization and job loss. This theoretical framework was mainly used to explain the relative spatial indeterminacy of new industries' localization patterns and fitted well with empirical observations of new innovative regions overtaking the position of old, declining industrial regions (Scott and Storper, 1987).

This is much in line with Perez and Soete's (1988) prominent paper on developing countries' capability to catch up in technology. They argue that four components influence the cost and capability of firms in a given country, or in this case a region, to enter a technological trajectory. The four components consist of fixed investments costs, scientific and technical knowledge, skills and experience (in management, production, marketing, etc.), and a set of locational advantages. These components are likely to vary depending on the nature of the technology and on the stage of technological evolution understood as phases in the technology's lifecycle (Perez and Soete, 1988). In the introduction phase, which is in focus for this paper, the level of scientific and technical knowledge and the level of locational advantages (externalities) are relatively high for firms to be able to enter the emerging technological trajectory, whereas the initial fixed investment costs and the experience and skills in managing, production, marketing, etc., are assumed to increase with a higher level of maturity of the technology. Perez and Soete argue, just as Boschma (2007), that it is "(…) absurd to assume that a firm can start with zero previous knowledge" (Perez and Soete, 1988, 466).

Perez and Soete's contribution on countries' capability to catch up in technology can be applied to regional economies at the sub-national level and their capability to enter into a radically new regional industrial path. In the early phase of radical technology development, two components in particular are of great importance: a minimum level of firm-bound scientific and technical knowledge within the technological knowledge base, and an advantageous location close to university research and researchers that can assist in the buildup of a new knowledge base. Consequently, it can be argued that the total knowledge base of a region, as an expression of firm-bound knowledge and other localized knowledge sources (e.g., universities and research institutes), has great influence on which radically new regional industrial paths will emerge within a given region.

Clearly, building new industries in regional economies is a complicated matter and cannot be ascribed to the regional composition of knowledge fields alone. We know from innovation system studies that the process of building new industries requires not only the accumulation of scientific and technological competences but also the altering of institutions and networks (Dalum et al., 1999; Lundvall, 1992). Other factors of institutional, cultural, political, and social character influence the development of new technological trajectories by creating favorable conditions for the technology, e.g., inducing knowledge diffusion among actors in the region and providing economic incentives to invest in R&D. This is also the case for fuel cell technology development (Madsen and Andersen, 2010). Such factors are clearly of immense importance, and I suggest by no means any deterministic relationship between the knowledge base of a given region and the emergence of a new industry. Nevertheless, this paper is dedicated to enquiries into the cognitive dimension of technological development, which is obviously a crucial element in the early years of a technology's evolution. In fact it is plausible to argue that specific localized knowledge required to enter a technology is a prerequisite for a region to succeed in the development of new regional industrial paths based upon radical technology.

Regional branching: an evolutionary approach

Boschma and Frenken (2011) employ the evolutionary metaphor 'regional branching' to illustrate that new industry grows out of the existing industrial structure within a region. Regional branching happens either when a new industry grows out of an existing industry or when knowledge and competences from a combination of sectors are brought together to form the development of a new industry.

The concept of regional branching builds on two ideas from the field of economic geography. First and foremost is that knowledge tends to spill over in spatial proximity rather than globally, as shown by the literature on localized knowledge spillover (Jaffe et al., 1993; Feldman, 1999; Anselin et al., 1997; Audretsch and Feldman, 1996; Maurseth and Verspagen, 2002). Several localized mechanisms[2] are argued to induce

[2] Neffke et al. (forthcoming) point to four mechanisms that play this role and at the same time tend to be regionally bounded (albeit not exclusively). These are firm diversification, spinoffs, labor mobility, and social networking. To this list we can add collaborative R&D projects and university startups, which seem to play an important role for fuel cell technology development.

knowledge spillover locally, leading to the process of regional branching. The common characteristic of these mechanisms is that they function as localized channels for knowledge transfers from existing industries and universities to the emerging industry.

Secondly, positive externalities of knowledge in a given field are more likely to spill over to third parties working in the same field (Antonelli, 2001). In other words, localized knowledge sharing and transfers are enhanced by 'technological relatedness' between sectors (Boschma and Frenken, 2011; Neffke and Svensson Henning, 2008), where technological relatedness is understood as an appropriate balance between cognitive proximity and distance (Nooteboom, 1999).

Empirically, 'regional branching' has found support from a number of studies when it comes to exploring the concept of regional path dependency in general, but has received less attention in the effort to understand the 'place dependency' (Martin and Sunley, 2006) of radical industrial paths. Previous studies have shown how regions develop along coherent industrial paths. Neffke, Henning, and Boschma (2011) demonstrate how Swedish regions develop along a somewhat coherent industrial path where industries have a higher probability to enter regions where the regional industrial structure is technologically related to that industry, and existing industries without relatedness to the region's industry have higher probability to exit. Moreover, Essletzbichler and Winther (1999) demonstrate that Danish regions develop along different technological trajectories in the food processing industry. When it comes to how radically new industries build on competences from old industries, Klepper and Simons' study (2000) demonstrates that successful television producers were experienced radio producers prior to entering the television industry, indicating a high level of complementarity in competences and routines between the two industries. Similarly, the study of Boschma and Wenting (2007) confirms that technological relatedness to the regional knowledge base plays a large role in the localization of the British car industry, and that the process in particular was driven by spinoffs from related industries.

The objective of this paper is twofold. First, the paper aims to test whether or not regions branch as a consequence of technological relatedness between preexisting regional generic resources and new radical innovations. Radical innovations build on a new set of scientific and technical principles (Arthur, 2009), which breaks with incumbent technological trajectories and lays the seeds for the creation of new paths. However, once the scientific and technical principles are discovered and the new technological trajectory takes shape by the buildup of a new knowledge base, actors draw on complementary knowledge assets from related disciplines and activities to improve the functionality of the technology. This paper argues that, because of the localized channels of knowledge transfers, regions with knowledge bases technologically related to the emerging knowledge base of a given radical technology have a higher probability of branching into industrial paths that build upon that particular radical technology.

A second objective is to expand our understanding of the character of such regional generic resources. It is claimed that new industry development benefits from a certain combination of generic resources, such as basic knowledge and skills (Boschma and van der Knaap, 1997). In the analysis that follows, the nature of these resources is decomposed beyond industrial classes. However, fuel cell technology is first described in more detail in the next section.

3. The case of fuel cell technology

Fuel cell technologies are seen as one of many alternatives to replace incumbent fossil fuel–based energy technologies. Fuel cells are somewhat generic in the sense that there is potentially a wide range of application opportunities across a variety of sectors (e.g., vehicles, combined heat and power systems, back-up units, auxiliary power units, laptops, mobile phones, hearing aids). Among the positive environmental effects of fuel cells are their high fuel efficiency and their exhaust being pure water, providing both local and global environmental benefits above the incumbent technologies (provided that the fuel is produced from renewable energy sources).

It is important to highlight the following five characteristics of the fuel cell technology when trying to understand the localization patterns of the new industry. First, its knowledge base is highly complex, serving therefore as a good example of a modern, emerging technology. Dibiaggio and Nasiriyar (2009) show that the fuel cell knowledge base became more and more complex up until 2002 as the number of new knowledge fields and new combinations of using distinctive knowledge fields kept rising.

Second, there are today several types of fuel cells, indicating that a dominant design has not yet been 'decided' upon. The different types of fuel cells vary in their advantages depending on the application option; however, studies (Brown et al., 2007) indicate that an *elimination* process has begun, keeping the proton exchange membrane fuel cell (PEMFC) and the solid oxid fuel cell (SOFC) in the field of interest for most companies. In this analysis the different types of fuel cells are analyzed together, even though there might be slight differences in the respective knowledge bases, mainly as a result of the use of different electrolytes, e.g., knowledge about ceramics plays a larger role in SOFC development where polymer compounds are important for PEMFC development. In any case, the lack of a dominant design indicates that the technology is in its very early development stage.

A third characteristic is that fuel cell technology, for some applications, is infrastructure dependent. This means that the validation of technology needs infrastructure support, for instance, hydrogen fueling stations and distribution systems. This dependency on infrastructure development might have consequences for the learning processes and their geographical embeddedness.

The infrastructure dependency points to a fourth characteristic: technological innovation in fuel cells is systemic. This implies that innovation hardly takes place in a single company but instead requires cooperation and coordination along the whole value chain.

Finally, the demand side is characterized by a strong policy drive expressed in visions such as 'the hydrogen economy' (Rifkin, 2004). On the positive side this implies a lot of financial support to R&D projects and to demonstrate and test the technology in real-life surroundings. On the negative side it creates immense uncertainty because a too strong dependency on political goodwill makes the innovation system vulnerable to changes on the political agenda.

4. Method, data, and the model

The general idea of this paper is to investigate the relationship between the knowledge base of a given region and the localization patterns of the emerging industry that is developing based on radical fuel cell technology. The intangible nature of knowledge makes it clearly difficult to measure its quantity (or quality for that matter) in any direct way (Foray 2004). Patent statistics is a widely used approach in quantitative studies to measure levels of competences for different units of analysis (see, e.g., Patel and Pavitt (1997) for large firms, and Zucker et al. (2007) for regions). The limitations in using patent data to measure knowledge production have also been widely criticized, although the critique has mainly targeted the use of patents to measure innovation. Here, I only discuss the limitations in using patent applications as a source of knowledge production.

Using patent applications as a measure for knowledge production will always be an imperfect measure for several reasons. First, patents are codified knowledge, whereas a high proportion of knowledge produced in firms, universities, and research institutes are tacit. Following Patel and Pavitt (1997), however, the two forms of knowledge are complementary rather than substitutes. For example, tacit knowledge is needed to understand and absorb information from patent applications, and vice versa. Second, a lot of knowledge production with scientific and technical content is not recorded by patent applications. And third, using the count of patent applications tends to obscure the variations in the quality of knowledge covered by patents (Zucker et al., 2007). Nevertheless, for the purpose of this study patent applications are considered the most appropriate measure, given their relative homogenous, detailed, and consistent recording of knowledge production.

Data

The OECD, REGPAT database, June 2010 is the main data source used. This database is a comprehensive attempt to regionalize patent applications filed under the Patent Cooperation Treaty (PCT) at international phase designated to the European Patent Office. A general reason for choosing PCT applications is that they are considered to contain the least country-based bias, because they represent international patent applications.

For the specific case of fuel cell patenting, the PCT dataset is preferable for two reasons. First, as in other fields patenting is a highly used strategy for firms to protect their knowledge assets in the fuel cell field (Avadikyan et al., 2003; Arechavala-Vargas et al., 2009). Because of the technology area's immaturity and the immense uncertainty about what the future may bring, firms that have invested heavily in this new technology are extremely concerned about protecting their knowledge.[3] Due to the technology's early stage of evolution, firms do not often have ready products (applied knowledge) or skills in manufacturing; technological knowledge is their main asset.

Second, due to the fact that firms within the fuel cell industry see themselves as global players,[4] it is appropriate to assume that they make use of the PCT system when applying for patents, because this gives

[3] This concern is not only about the technological knowledge, but also about information on suppliers and collaboration partners, which most fuel cell firms do not want to reveal.
[4] The author's own interviews with fuel cell stack and system developers and from Arechavala-Vargas et al. (2009).

them the possibility to seek patent protection for an invention in each of a large number of countries at the same time (Arechavala-Vargas et al., 2009).

The OECD REGPAT has regionalized the addresses of both applicants and inventors into two hierarchical territorial levels: territorial level 2 (TL2) and territorial level 3 (TL3).[5] In this study the sample of analysis refers to 250 NUTS2 regions across Europe, which correspond to TL2.[6] All patent data used are based on the inventor's address, since this is considered to be closest to the place of invention, and priority year, since this is considered to be closest to the time of invention.

Identifying the knowledge base of fuel cell technology

The main interest is to define and measure (1) fuel cell knowledge production for a given region in a given year; (2) the knowledge base of fuel cell technology, defined as a set of knowledge fields indicating technologically related knowledge fields; and (3) the frequency of each of the fuel cell–related knowledge fields in all non–fuel cell knowledge production for a given region in a given year. First, the knowledge base of fuel cell technology (2) is defined.

To identify the fuel cell knowledge base, all patents classified in accordance with the International Patent Classification (IPC)[7] system covering fuel cell technology were extracted from the dataset. This was done rather precisely by using IPC-main groups (7-digits), H01M008 ("Fuel cells, manufactures thereof"). The analysis

[5] TL2 is the most aggregated level, and consists of 335 regions and corresponds for most EU countries to the NUTS 2 classifications. In the case where TL2 does not directly correspond with NUTS2, data have been summarized based on the TL3 classifications. For Denmark, NUTS1 was used since the structural reform of 2007 has created inconsistency in the continuity of the data series.

[6] Due to lack of some regional data (mainly governmental expenditures on R&D, used as control variable) only regions from following countries are included: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, the Netherlands, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, and the United Kingdom. Furthermore, two Italian autonomous regions and French Guadalupe have been dropped.

[7] The IPC is a hierarchical category system developed by the World Intellectual Property Organization (WIPO) for classifying patents and patent applications. Patents cover a broad area of technology fields, and each field can be further divided into subtopics until a reasonable level of specialization is reached. The classification consists of five hierarchical levels: sections (A – H), classes (3 digits), subclasses (4 digits), main groups (7 digits), and subgroups (9-digits).

focuses on the period 1992-2007; 1992 is the year the main patenting (and development) activity in fuel cells took off, and 2007 is the latest complete year in the database. For this period the dataset contains 8,572 fuel cell patent applications[8] defined by IPC-code H01M008. This paper concentrates on the regional dynamics of fuel cell development in Europe and limits therefore the analysis to patent applications filed by inventors localized in a sample of European regions, totaling 2,429 patent applications.

To measure the knowledge base of fuel cell technology I identify a set of knowledge fields that together form the technological knowledge base of fuel cell technology. These are identified by IPC-codes that are co-classified with the European sample of fuel cell patent applications. A patent application is often assigned with more than one IPC-code, reflecting every single knowledge fields the patent covers. These knowledge fields are somehow involved in the generation of fuel cell knowledge. Therefore, there is a good reason to assume that knowledge fields (IPC-codes) that are co-classified with fuel cell patent applications form part of the fuel cell knowledge base.

The co-classified knowledge fields are aggregated at the level of subclasses (4 digits).[9] This shows that 312 out of 628 possible IPC subclasses are co-classified with the IPC-code for fuel cells. However, a large number of the 312 IPC subclasses occur only a few times over the whole period. Thus, to keep the analysis relatively simple only IPC subclasses with a share >1 pct. have been included as forming part of the fuel cell knowledge base.

-- Table 1 about here --

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[8] The OECD REGPAT database covers 42 countries, 30 being OECD members: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, South Korea, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Sweden, Switzerland, Turkey, the United Kingdom, and the United States.

[9] As all patents and patent applications are classified with IPC-codes at the subgroup level (9 digits) some co-classifications fall within the same subclass (4 digits). If this is the case the subclass is only counted once.

Table 1 provides a description of the eight knowledge fields[10] that together form part of the fuel cell knowledge base and their relevance for fuel cell technology.

The composition of the knowledge fields at different times can be seen in Figure 1. The first column illustrates the distribution for all years in the period 1992-2007, and the remaining five columns show the variation in three-year periods. The figure illustrates that the knowledge base is relatively stable from 1992 to 2007. We can note, however, that the share of 'electrolytic processes' decreases over time while the share of 'electrical vehicles' and 'circuit arrangements and storage' increases.

- Figure 1 about here -

The identification of the fuel cell knowledge base provides at the same time the identification of knowledge fields that are technologically related to the emerging fuel cell industry. The level of knowledge production within each of these eight areas for each given region for each year serves as the independent variable and is described in more detail below. First the dependent variable, the level of fuel cell knowledge production (1), is defined.

The dependent variable: fuel cell knowledge production

The dependent variable in the analysis is fuel cell knowledge produced in given regions at given times. It is measured as fuel cell patenting activity (FCpt) filed under the PCT, and defined as above (all patent applications with IPC-code equal to H01M008, "Fuel cells and manufactures thereof"). The patents are ascribed at the regional level using a non-fractional count. In the OECD REGPAT database the fractional count takes into consideration that for each patent application several inventors with different regional residence may be

[10] Originally, this approach to identify the knowledge base of fuel cell technology revealed 13 knowledge fields with a co-classification share > 1. Because a correlation matrix revealed correlation coefficients higher than 70% for 6 of the knowledge fields (B01D, B01J, C01B, C08G, C08J, C08L), these were joined into the overall knowledge field of 'Physical and chemical processes' to avoid causing multicollinearity in the model.

behind the invention, and hence only ascribes a fraction of each patent application to the specific region where the inventor resides. I argue, however, that knowledge is a non-divisible asset and since the purpose of this study is to measure knowledge production at the regional level, I use non-fractional counts, i.e., on the occasion where multiple inventors from different regions are behind a patent application the same patent application is assigned to each of the regions involved.

Since fuel cell technology is still an immature technology, the number of FCpt for some regions is small, particularly in the early period. Therefore, FCpt is calculated as the sum of three consecutive years for each region for each year in the period 1992-2007. In this way, the model also takes into account the time for fuel cell–related knowledge to be absorbed and utilized in the generation of fuel cell knowledge.

Independent variable: technological relatedness

The independent variables are measures of fuel cell–related knowledge for each region. Based on the knowledge base of fuel cell technology (the eight knowledge fields identified in Table 1), two measures of regional assets in fuel cell–related knowledge fields are calculated. The first measure of fuel cell technological relatedness (FC-TR) consists basically of eight measures indicating the level of knowledge production within each of the identified knowledge fields for each region for each year. It is calculated for all non–fuel cell patent applications, i.e., all fuel cell patent applications are withdrawn from the database before aggregating the frequency of patent applications within the selected IPC subclasses. Two further steps were taken in preparing the FC-TR measures. Since regions differ in their total level of knowledge production (all patent applications filed under the PCT regardless of IPC-codes) a first step was taken to make FC-TR comparable by relating the knowledge produced within each of the eight knowledge fields to the total patent activity of the region. This is a way of controlling for large differences that exist between the regions' level of knowledge production and which could explain the differences in levels of fuel cell knowledge production.[11] Second, following Zucker et al. (2007), the figures were computed by cumulating counts for all previous years, and discounting by 20% annually to reflect depreciation of knowledge.

The second measure of fuel cell technological relatedness (FC-TR-DIV) indicates the diversity among the eight knowledge fields. FC-TR-DIV is calculated as a categorical variable taking the values 0 to 8, 0 if none of the fuel cell–related knowledge fields are present, and 8 if all of them are present in a given region in a given year. The higher the FC-TR-DIV, the higher the degree of diversity within fuel cell–related knowledge that characterizes the knowledge base of a region. In this way FC-TR-DIV can be interpreted as an indicator of the degree of technological relatedness between a region's knowledge base and a certain technology, in this case fuel cell technology.

A number of controls have also been included:

Governmental Expenditures on R&D (GERD)

The availability of public R&D expenditures is likely to affect the production of fuel cell knowledge. Thus, Governmental Expenditures on R&D (GERD) at the regional level (NUTS2) is included as a control. At the same time a high level of GERD is likely also to affect the total level of knowledge production in a region. In fact, GERD is strongly correlated with total number of patents (0.76), so this is assumed to be a good additional control for both the availability of public R&D funding in a region and the total level of knowledge produced (patented). Data were downloaded from Eurostat. For some regions, however, data were not comprehensive and it became necessary to extrapolate for missing years.

[11] It is not possible to control for total level of patenting by including it as a control variable, because it would cause multicollinearity in the model. A 'variance inflation factor' analysis of the dataset showed that the variable 'total patent count' exceeded the value 12.

Population

A population measure was included to control for the size of the region, since it is assumed that larger regions will generate more knowledge.

Lagged dependent variable

Furthermore, a lagged dependent variable (LAG.1 FC) was included to account for the effect of fuel cell knowledge produced in foregoing years. The lagged dependent variable was constructed in similar ways as the FC-TR measure, i.e., cumulated counts for all previous years, and discounting by 20% annually to reflect depreciation of fuel cell knowledge.

The model

The analysis is carried out on a balanced panel data set comprising the years 1992-2007 and 250 European NUTS2 regions. Since the dependent variable is a running aggregate of three consecutive years and I include a lagged dependent variable, the panel covers in fact only 13 three-year periods and independent variables for the years 1993-2005. Most of the regions have a relatively low count of FCpt while a smaller tail has much higher counts. FCpt is clearly a limited dependent count variable, which suggests that the appropriate model is a count model such as the Poisson or negative binomial model, following Hausman et al. (1984). While the Poisson model requires the variance of the dependent variable to equal its mean, the distribution of FCpt (see Figure 2) reveals clear overdispersion – a violation of the mean-variance equality restriction. This suggests using the negative binomial model that allows for heterogeneity on the mean.

- Figure 2 about here -

To control for unobserved heterogeneity we run the model with fixed effects. Introducing fixed effects to the model builds on the assumption that there are some time-independent regional effects that correlate with the explanatory variables. Moreover, a Hausman test (1978) confirmed our choice over the random effects. The fixed effect has another consequence for the model because it only includes groups (regions) with FCpt values >0. Hence, the model drops 76 groups (regions), and the analysis is carried out on the remaining 172 regions.[12] Each variable (see list of variables in Table 2) is therefore measured for each year in the period 1993-2005 for each of the remaining 172 regions, hence N = 13 years x 172 regions = 2236.

- Table 2 around here –

5. Results

Table 3 shows the results of the negative binomial regression with fixed effects on the relationship between (1) controls, and (2) the FC-TR measure and the dependent variable FCpt. Model (1) confirms that governmental R&D expenses are positively correlated with the level of fuel cell knowledge production (FCpt). However, the size of the region measured by population reveals a negative relationship. This could be due to the fixed effect, but running the same model with random effects shows similar results. This could be an indication that fuel cell knowledge production takes place outside the most populated regions. The signs and significance for both controls are confirmed in models (2) and (3).

- Table 3 about here –

The overall results revealed in model (2) show that fuel cell knowledge production (FCpt) is higher in regions with fuel cell–related knowledge fields, although some knowledge fields are more important than others. In total, five out of eight technology areas have a positive significant impact on the regional production of fuel cell knowledge, hence indicating a positive spatial relationship. The technology fields 'chemical or physical processes', 'conversion of chemical energy into electrical energy', 'cables, conductors, insulators', 'materials

[12] NUTS2 codes for the 76 regions the model drops because of no fuel cell patenting activity: AT32, AT34, BE34, BE35, CZ02-CZ08, ES11-ES13, ES53, ES62, FI13, FI1A, FR21, FR83, GR11-GR14, GR21, GR22, GR24, GR25, GR41-GR43, HU21-HU23, HU31, HU32, IE01, ITC2, ITD1, ITD2, ITF2, ITF4-ITF6, ITG2, NL11, NL23, NL34, NO07, PL11, PL21, PL31-PL34, PL41-43, PL51, PL52, PL61-PL63, PT11, PT15, PT18, SE21, SE33, SK01-SK04, UKF3, UKJ4, UKK3.

e.g. ceramics', and 'analyzing materials' all have a positive significant association with the production of fuel cell knowledge in the consecutive three years. All these knowledge fields are central to the functioning of fuel cells. The first two refer to the main processes that take place in the core of the fuel cell: chemical process of energy conversion. The third knowledge field indicates the importance of knowledge in conductive materials to assure a high efficiency in the fuel cell's production of electricity. The knowledge field 'ceramic materials' is mainly of importance for solid oxid fuel cells where the electrolyte is made of ceramics. The last positive significant knowledge field, 'analyzing materials', refers mainly to the determination of the materials' physical and chemical properties and makes the developers capable of monitoring and testing any technological progress.

Three knowledge fields show no significant relationship to the production of fuel cell knowledge. First, the knowledge field 'electrolytic processes' reveals no significant relationship. Since electrolysis is the inversed chemical process of what takes place in the fuel cell, this could indicate that the two fields have started growing into two independent technological trajectories concurrently with an increased specialization. Second, the field 'electrical vehicles' is not significant to the production of fuel cell knowledge. This might indicate that most development within electrical vehicles takes place independently of fuel cell development because most electrical vehicles rely solely on batteries as the energy converter technology. In some cases fuel cell systems are perceived as sub-systems to the electrical vehicles, but the contrary does not apply. Hence, knowledge of electrical vehicles is not necessarily spatially associated with fuel cell knowledge. The knowledge field 'circuit arrangements, and storing' is a third field that shows no significant relationship to fuel cell knowledge production. The reason could be that circuit arrangements and systems for energy storing have the character of being mere supportive arrangements to the core functions of the fuel cell.

Table 4 shows the results of the third model running the analysis on the fuel cell technologically related diversity (FC-TR-DIV) measure. The results confirm that the more knowledge fields that are represented in a region, i.e., the larger the diversity of fuel cell–related knowledge fields, the larger the probability of generating fuel cell knowledge in the following three years.

- Table 4 about here -

Model (3) shows in fact that regions with three or more fuel cell–related knowledge fields have a significantly higher probability of generating fuel cell knowledge, and that the correlation coefficients are increasing by the number of knowledge fields present in a given region. This indicates that the higher the degree of technological relatedness between the regional knowledge base and that of an emerging industry, the higher the probability that a new industry is to emerge in that region.

6. Conclusion

The objective of this paper has been, firstly, to pursue the evolutionary thesis that regions develop along technological trajectories also in the case of radically new industrial paths. The main contribution has been to test empirically if the creation of new regional industrial paths is driven by knowledge spillover processes enhanced by technological relatedness to preexisting regional economic activities, which the findings support.

Secondly, the objective has been to expand our knowledge on the character of such location-specific resources. Previous studies have made use of industry classifications, but the great advantage of the current study is it provides more detailed proof of the relationship between a region's knowledge base and its technological relatedness to an emerging technology. The empirical results can be summarized by the following two points: 1) the analysis points towards specific technologically related knowledge fields that are significantly co-located with the generation of fuel cell development, and 2) it reveals that the higher the degree of technological relatedness present in a given region, the higher the probability for a region to branch into fuel cell technological development.

Thirdly, the paper has developed a new measure of technological relatedness using regionalized patent databases, which seems to have certain advantages, in particular when studying new technology areas that are not recognized by industrial classification systems (e.g., NACE).

These findings raise one central question: what causes the evolutionary processes of the creation of new variety at the regional level? The results here suggest that this process is highly localized in space (at least within the borders of NUTS2 regions) but do not reveal how much of this process can be ascribed to firm diversification (specific firm-bound scientific and technical knowledge), spinoffs, or locational advantages causing positive externalities. Boschma and Wenting (2007) show that spinoff processes play a larger role than locational economies in the early years of industry development. If future research can provide further evidence of such character it would be extremely valuable for understanding the evolutionary development of new industries and their spatial manifestation.

The results also raise questions of a more fundamental character: the level of discontinuity of radical technological change and its implications for new regional industrial paths. As pointed out in section 2, the discontinuous nature of radical technology has caused economic geographers to argue that new (radical) industries develop independently from preexisting industrial structures. The findings of this paper suggest that even in the case of radical technology development, knowledge production is also highly cumulative and builds on preexisting localized scientific and technical knowledge resources, which implies that the emergence of radically new industrial paths is highly place dependent (Martin and Sunley, 2006).

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References

Anselin L., Varga A., Acs Z. (1997) Local geographic spillovers between university research and high technology innovations. *Journal of Urban Economics*, 42: 422-448.

Antonelli C. (2001) *The microeconomics of technological systems*. USA: Oxford University Press.

Arechavala-Vargas R., Díaz-Pérez C., Holbrook J.A. (2009) Globalization of innovation and dynamics of a regional innovation network: The case of the Canadian Fuel Cell Cluster. 2009 Atlanta Conference on Science and Innovation Policy, IEEE, Georgia Institute of Technology Global Learning Center, Atlanta, 2-3 October: 1-7.

Arthur W.B. (2009) *The nature of technology: What it is and how it evolves*. New York: Free Press.

Audretsch D.B., Feldman M.P. (1996) R&D Spillovers and the Geography of Innovation and Production. *The American Economic Review*, 86: 630-640.

Avadikyan A., Cohendet P., Héraud J. (2003) Introduction in A. Avadikyan and P. Cohendet. *The economic dynamics of fuel cell technologies*. Berlin Heidelberg: Springer Verlag, 1-20.

Boschma, R.A. (1997), New industries and windows of locational opportunity. A long-term analysis of Belgium, Erdkunde, vol. 51, 12-22.

Boschma R.A. (2007) Path creation, path dependence and regional development. Path Dependence and the Evolution of City Regional Development, 11, Papers Presented at a Workshop at St. Catharine's College, Cambridge University, Cambridge.

Boschma R., Frenken K. (2011) Technological relatedness, related variety and economic geography. In P. Cooke, B. Asheim, R. Boschma, R. Martin, D. Schwartz and F. Todtling (eds), Chapter 14, *The Handbook on Regional Innovation and Growth*. Cheltenham: Edward Elgar.

Boschma R., Martin R. (2007) Editorial: Constructing an evolutionary economic geography. *Journal of Economic Geography*, 7 (5), 537-548.

Boschma R., Martin R. (2010) *Handbook of Evolutionary Economic Geography*. Cheltenham: Edward Elgar.

Boschma R.A., van der Knaap B. (1997). New technology and windows of locational opportunity: indeterminacy, creativity and chance. In J. Reijnders, *Economics and Evolution*. Cheltenham UK: Edward Elgar, 171-202.

Boschma R.A., Lambooy J.G. (1999) Evolutionary economics and economic geography. *Journal of evolutionary economics*, 9: 411-429.

Boschma R.A., Wenting R. (2007) The spatial evolution of the British automobile industry: Does location matter? *Industrial and Corporate Change*, 16: 213-238.

Bourgeois B., Mima S. (2003) Rationales for co-operation between firms and States within an emerging radical innovation. In A. Avadikyan, P. Cohendet and J. Héraud, *The Economic dynamics of fuel cell technologies*. Berlin, Heidelberg, New York: Springer Verlag, 79-113.

Brown J., Hendry C., Harborne P. (2007) Developing Radical Technology for Sustainable Energy Markets. *International Small Business Journal*, 25: 603-629.

Dalum B., Holmén M., Jacobsson S., Praest M., Rickne A., Villumsen G. (1999) Changing the regional system of innovation in J. Fagerberg, P. Guerrieri and B. Verspagen (eds), Chapter 14, *The economic challenge for Europe: adapting to innovation based growth*. Cheltenham: Edward Elgar Publishing.

Dibiaggio L., Nasiriyar M. (2009) Rate and dimensions of the technological knowledge base underlying fuel cell innovations. Evidence from patent data. In S. Poguts, A. Russo and P. Migliavacca, *Innovation, markets and sustainable energy: the challenge of hydrogen and fuel cells*. Cheltenham, UK: Edward Elgar Pub, 87-101.

Dosi G. (1982) Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technical change. *Research policy*, 11: 147-162.

Dosi G. (1988) The nature of the innovative process. In G. Dosi, C. Freeman, R. Nelson, G. Silverberg and L. Soete, *Technical change and economic theory*. London: Pinter Publishers, 221-238.

Dosi G., Orsenigo L. (1988) Coordination and transformation: an overview of structures, behaviours and change in evolutionary environments. In G. Dosi, C. Freeman, R.R. Nelson, G. Silverberg and L. Soete, *Technical Change and Economic Theory*. London: Pinter Publishers, 13-37.

Foray D. (2004) *Economics of knowledge*. Cambridge, MA: The MIT Press.

Essletzbichler J., Rigby D.L. (2007) Exploring evolutionary economic geographies. *Journal of Economic Geography*, 7: 549-571.

Essletzbichler J., Winther L. (1999) Regional technological change and path dependency in the Danish food processing industry. *Geografiska Annaler: Series B, Human Geography*, 81: 179-196.

Feldman M.P. (1999) The new economics of innovation, spillovers and agglomeration: a review of empirical studies. *Economics of innovation and new technology*, 8: 5-25.

Freeman C. (1994) The economics of technical change. *Cambridge journal of economics*, 18: 463-514.

Freeman C., Perez C. (1988) Structural crises of adjustment, business cycles and investment behaviour. In G. Dosi, C. Freeman, R.R. Nelson, G. Silverberg and L. Soete, *Technical change and economic theory*. London: Pinter Publishers, 38-66.

Garcia R., Calantone R. (2002) A critical look at technological innovation typology and innovativeness terminology: a literature review. *Journal of Product Innovation Management*, 19: 110-132.

Grabher G. (2009) Yet another turn? The evolutionary project in economic geography. *Economic Geography*, 85: 119-127.

Hausman J.A. (1978) Specification tests in econometrics. *Econometrica: Journal of the Econometric Society*, 46: 1251-1271.

Hausman J.A., Hall B.H., Griliches Z. (1984) Econometric models for count data with an application to the patents-R&D relationship. *Econometrica*, 52: 909-938.

Jaffe A.B., Trajtenberg M., Henderson R. (1993) Geographic localization of knowledge spillovers as evidenced by patent citations. *The Quarterly journal of Economics*, 108: 577-598.

Klepper S., Simons K.L. (2000) Dominance by birthright: entry of prior radio producers and competitive ramifications in the US television receiver industry. *Strategic Management Journal*, 21: 997-1016.

Lundvall B.Å. (1992) *National Innovation Systems: towards a theory of innovation and interactive learning*. London: Pinter.

Madsen A.N., Andersen P.D. (2010) Innovative regions and industrial clusters in hydrogen and fuel cell technology. *Energy Policy*, 38: 5372-5381.

Martin R., Sunley P. (2006) Path dependence and regional economic evolution. *Journal of Economic Geography*, 6: 395-437.

Maurseth P.B., Verspagen B. (2002) Knowledge spillovers in Europe: a patent citations analysis. *The Scandinavian journal of economics*, 104: 531-545.

Neffke F., Henning M., Boschma R. (2011) How do regions diversify over time? Industry relatedness and the development of new growth paths in regions. *Economic Geography* 87(3), 237-265.

Neffke F., Svensson Henning M. (2008) Revealed relatedness: Mapping industry space. Papers in Evolutionary Economic Geography, #08.19, Utrecht, University of Utrecht.

Nelson R.R., Winter S.G. (1982) *An evolutionary theory of economic change*. Cambridge, Massachusetts and London, England: The Belknap Press of Harvard University Press.

Nooteboom B. (1999) Innovation, learning and industrial organisation. *Cambridge Journal of Economics*, 23: 127-150.

OECD REGPAT database. (June 2010), REGPAT database.

Patel P., Pavitt K. (1997) The technological competencies of the world's largest firms: Complex and path-dependent, but not much variety. *Research Policy*, 26: 141-156.

Perez C., Soete L. (1988) Catching up in technology: entry barriers and windows of opportunity. In G. Dosi, C. Freeman, R.R. Nelson, G. Silverberg and L. Soete, *Technical Change and Economic Theory*. London: Pinter Publishers, 458-479.

Rifkin J. (2004) *The hydrogen economy*. New York: Tarcher/Penguin.

Scott A.J., Storper M. (1987) High technology industry and regional development: a theoretical critique and reconstruction. *International Social Science Journal*, 39: 215-232.

Storper M., Walker R. (1989) *The capitalist imperative: Territory, technology, and industrial growth*. New York: Wiley-Blackwell.

Zucker L.G., Darby M.R., Furner J., Liu R.C., Ma H. (2007) Minerva unbound: Knowledge stocks, knowledge flows and new knowledge production. *Research Policy*, 36: 850-863.

TABLE 1: EIGHT KNOWLEDGE FIELDS THAT TOGETHER COMPOSE THE KNOWLEDGE BASE OF FUEL CELL TECHNOLOGY IN THE YEARS 1992-2007

IPC	IPC name	Knowledge field	Relevance for fuel cell	Share**
*B01D, B01J, C01B, C08G, C08J, C08L**	*Catalysis, colloid, chemistry, separation, non-metallic elements, organic macromolecular compounds*	**Physical and chemical processes**	Physical and chemical processes cover the main processes that take place at the core of the fuel cell.	28.8 %
H01M	*Processes or means , e.g., batteries for the direct conversion of chemical energy into electrical energy*	**Direct conversion of chemical energy into electrical energy**	This is obviously one of the core knowledge fields in fuel cell development, since converting chemical energy into electrical energy is the key function of fuel cells.	23.1 %
H01B	*Cables, conductors, insulators, selection of materials for their conductive, insulating or dielectric properties*	**Cables, conductors, insulators**	The fact that fuel cells generate electricity makes electrical conductors, conductive materials, cables, insulators, etc., very central to the development of fuel cells.	4.3 %
C25B	*Electrolytic and electrophoretic processes for the production of non-metals, apparatus therefor*	**Electrolytic processes**	Electrolytic processes are the inversed reaction of what takes place in the fuel cell. In electrolysis, electricity generates gases, e.g., hydrogen.	3.4 %
B60L	*Electric equipment or propulsion of electrically propelled vehicles, electrodynamic brake systems for vehicles, in general*	**Electrical Vehicles**	The knowledge field of electrical vehicles is strongly related to fuel cell applications in the transport sector. Since fuel cells generate electricity, applied knowledge in vehicles will lie within this knowledge field.	2.0 %
C04B	*Lime, magnesia, slag, cements, compositions thereof, e.g., mortars, concrete or like building material, artificial stone, ceramics*	**Ceramics, materials**	Ceramics are used mainly in solid oxide fuel cells that have a ceramic (solid oxide) electrolyte.	1.7 %
G01N	*Investigating or analyzing materials by determining their chemical or physical properties*	**Analyzing materials**	The chemical and physical processes taking place in the heart of the fuel cell involve testing and measuring, as well as analyzing the effects of various materials, which are particularly important in the stage of development.	1.4 %
H02J	*Circuit arrangements or systems for supplying or distributing electric power, systems for storing electric energy*	**Circuit arrangements, energy storage**	This area is more peripheral to the key functions of fuel cells. Circuit arrangements and systems for energy storing are considered to be supportive arrangements.	1.3 %

* This knowledge field is the sum of six subclasses, since the correlation between them is >0.70 and would cause collinearity in the regression.

** The share indicates how large of the total co-classifications belong to the specific knowledge field.

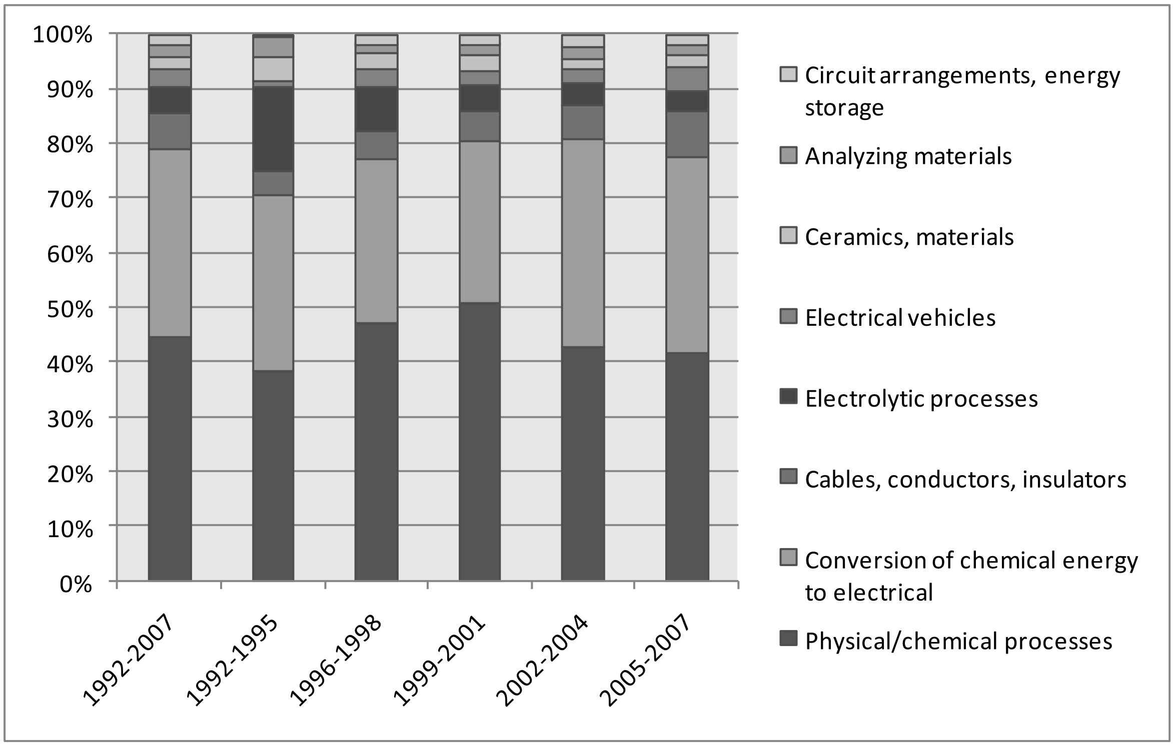

FIGURE 1: COMPOSITION OF THE FUEL CELL KNOWLEDGE BASE OVER TIME, SOURCE: OWN CALCULATIONS BASED ON OECD REGPAT, JUNE 2010,

TABLE 2: LIST OF VARIABLES FOR 172 NUTS2 REGIONS, YEARS 1993-2005

List of variables	**European NUTS2 regions**				
	N	Mean	S.D.	Min	Max
Fuel cell patenting	2236	1.36	4.67	0	82
Fuel cells (FCpt) (consecutive three yrs)	2236	4.61	14.16	0	232
FC TR					
Physical/chemical processes	2236	46.52	96.19	0	1,022
Conversion of chemical energy to electrical	2236	1.96	4.99	0	63
Cables, conductors, insulators	2236	1.61	3.98	0	73
Electrolytic processes	2236	0.60	1.95	0	39
Electrical vehicles	2236	0.59	2.41	0	34
Ceramics, materials	2236	3.65	7.28	0	73
Analyzing materials	2236	22.60	40.43	0	500
Circuit arrangements, energy storage	2236	1.38	3.73	0	60
FC-TR-DIV	2236	3.85	1.91	0	8
Controls:					
R&D exp.	2236	953.08	1,280.95	8.72	16,216.1
Population	2236	2,092,832	1,593,828	263,056	11,400,000

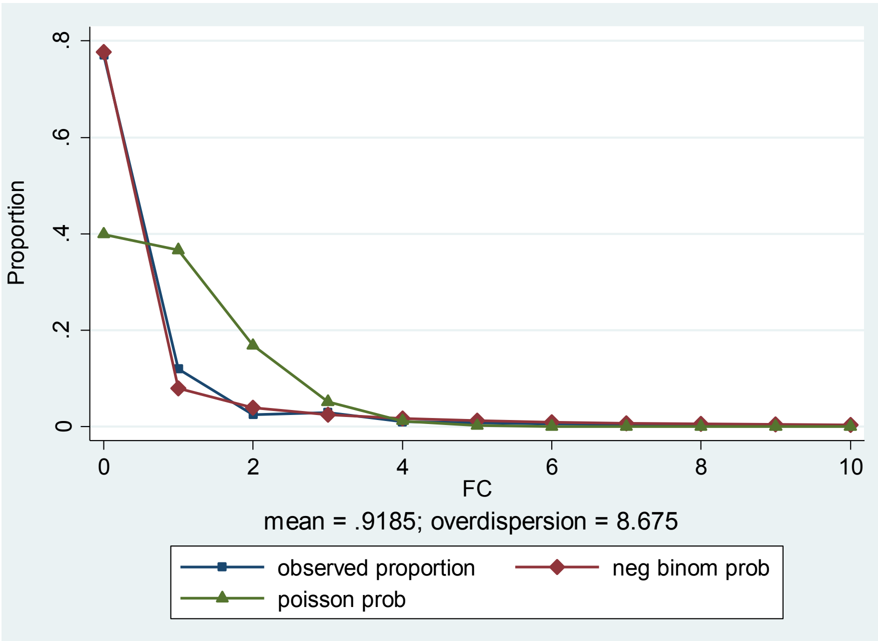

FIGURE 2: DISTRIBUTION OF OBSERVED PROPORTION AND ITS FITNESS TO POISSON AND NEGATIVE BINOMIAL, RESPECTIVELY.

TABLE 3: REGIONAL FUEL CELL TECHNOLOGICALLY RELATED KNOWLEDGE STOCK EFFECTS ON FUEL CELL PATENTING, NEGATIVE BINOMIAL REGRESSION WITH FIXED EFFECTS FOR EUROPEAN REGIONS (NUTS2), 1992-2007

	(1)	**(2)**
CONSTANT	11.627 (1.759)***	3.677 (2.081)*
LAG.1 FC		0.010 (0.001)***
FC-TR:		
CHEMICAL OR PHYSICAL PROCESSES		**0.486 (0.103)*** **
CONVERSION OF CHEMICAL ENERGY INTO ELECTRICAL ENERGY		**1.492 (0.644)** **
CABLES; CONDUCTORS; INSULATORS;		**5.532 (1.256)*** **
ELECTROLYTIC PROCESSES		-1.441 (2.399)
ELECTRICAL VEHICLES		-2.079 (2.801)
CERAMICS; MATERIAL		**1.301 (0.544)** **
ANALYZING MATERIALS		**2.547 (0.195)*** **
CIRCUIT ARRANGEMENT; STORING		2.466 (1.812)
R&D (LOG)	1.101 (0.076)***	0.620 (0.085)***
POPULATION (LOG)	-1.267 (0.139)***	-0.557 (0.163)***
N (Regions)	172	172

*** P < 0.001, ** P < 0.05, and * P < 0.1

TABLE 4: REGIONAL FUEL CELL TECHNOLOGICALLY RELATED DIVERSITY (FC-TR-DIV) EFFECTS ON FUEL CELL PATENTING, NEGATIVE BINOMIAL REGRESSION WITH FIXED EFFECTS FOR EUROPEAN REGIONS (NUTS2), 1992-2007

	(3)
Lag1_DV	-0.001 (0.001)**
FC-TR-DIV:	
1 out of 8	0.299 (0.348)
2 out of 8	0.258 (0.344)
3 out of 8	0.6560 (0.342)*
4 out of 8	0.818 (0.344)**
5 out of 8	1.128 (0.347)***
6 out of 8	1.192 (0.349)***
7 out of 8	1.398 (0.352)***
8 out of 8	1.667 (0.359)***
Constant	13.842 (1.932)***
R&D (LOG)	0.891 (0.095)***
Population (LOG)	-1.386 (0.156)***
N (Regions)	172

*** P < 0.001, ** P < 0.05, and * P < 0.1